A Study of the Unbalanced Alternating Current Bridge for Magnetic Analysis

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By
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DISSERTATION

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VITA

John Harold Lampe, son of Julius Gerhard Lampe and Florence Mae Lampe, was born in Baltimore, Md., December 1, 1896.

He received his elementary and secondary education in the Baltimore City Public Schools, graduating from the Baltimore Polytechnic Institute in June, 1915. In October, 1915, he matriculated at the Johns Hopkins University as a student in Electrical Engineering and graduated with the degree of Bachelor of Science in Engineering in June, 1918.

He immediately enlisted in the Signal Corps of the United States Army and served until January, 1919, being honorably discharged with the rank of Second Lieutenant, Air Service.

He was then employed in the laboratory of the Winchester Repeating Arms Co. at New Haven, Conn., where he worked under the direction of Dr. W. B. Kouwenhoven on magnetic analysis of rifle barrel steel and the development of flash light batteries.

In September, 1920, he returned to the Johns Hopkins University as Instructor in Electrical Engineering and part-time graduate student, receiving the degree of Master of Electrical Engineering in June, 1925. Since September, 1928, he has held the position of Associate in Electrical Engineering. Part time graduate work was continued and in the winter of 1929-30 he started experimental work under the supervision of Dr. W. B. Kouwenhoven. This work was continued throughout the year of 1930 and was completed in the spring of 1931.

His principal subject was Electrical Engineering and his first and second subordinates were Physics and Mathematics, respectively. During the course of graduate instruction, he studied under Dr. J. B. Whitehead, Dr. W. B. Kouwenhoven, and Dr. F. W. Lee of the Department of Electrical Engineering; Dr. J. S. Ames of the Department of Physics, Dr. A. Cohen of the Department of Mathematics, and Professor A. G. Christie of the Department of Mechanical Engineering.

He was employed at various times during the several summers by the Westinghouse Electric and Manufacturing Co., East Pittsburgh; the Chesapeake and Potomac Telephone Co., Washington, D. C.; and the Consolidated Gas, Electric Light and Power Company of Baltimore, Md. He has been actively engaged, since 1922, in teaching in the Department of Electrical Engineering of the Night Courses for Technical Workers of the Johns Hopkins University.

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THE UNBALANCED ALTERNATING CURRENT BRIDGE FOR MAGNETIC ANALYSIS II

BY W. B. KOUWENHOVEN[1] AND J. H. LAMPE[2]

SYNOPSIS

This paper presents a discussion of improvements in the unbalanced alternating-current bridge developed for the magnetic testing of specimens differing in cross-sectional area. The results show clearly that the improved bridge provides a simple means of separation of specimens of unequal cross-section into definite groups according to heat treatment.

The operation of the bridge was studied at various frequencies and it is definitely shown that flux penetration plays a part in its operation at 60 cycles. The paper further describes the investigations made with a view to increasing the sensitivity of the bridge. Data are given as to the best types of magnetizing solenoids to be used, the method of determining the most satisfactory values of the magnetomotive force, the proper values of the impedance of the arms of the bridge, and the improved operation obtained by using a constant alternating voltage across the bridge.

Finally, the results of a series of tests on knife blades are given and compared with those obtained with the bridge as originally developed. This comparison shows clearly very large increases in separation of specimens when using the improved bridge arrangement. The increased and definite separation of specimens makes possible a good correlation between their magnetic characteristics as measured in the bridge, and their Brinell hardness.

INTRODUCTION

Of all the methods of magnetic analysis for testing steel as to its quality or degree of heat treatment, the alternating-current methods seem to offer the best possibilities. These methods usually use a moving coil alternating-current galvanometer as a detector. The magnetic field of this type of galvanometer is set up by a separate field winding which carries current of the same frequency as that used in testing the specimens. By varying the phase of the current through the galvanometer field the deflection of the instrument may be made proportional to the magnetic flux in the specimen, the losses, or to any desired combination of these two.

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One of the authors described an alternating-current method in a paper presented before the Society last year.[1] In this method an unbalanced alternating-current bridge was used and it was discovered that at a certain phase setting of the galvanometer field, the readings of the bridge were independent of the cross-sectional area of the specimens tested. The present paper deals with a further study of the unbalanced alternating current bridge with reference to the best type of test coil, the effect of variations in bridge arrangements, and other methods of increasing the sensitivity. This study has led to a bridge which possesses high sensitivity and which gives a large and definite separation between specimens differing slightly in quality.

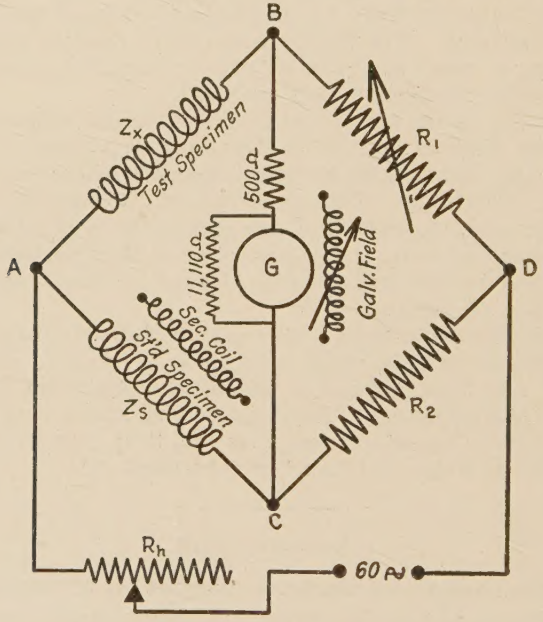

FIG. 1.—Diagram of Bridge Circuit.

THE BRIDGE

A brief description of the unbalanced alternating-current bridge is repeated here to familiarize the reader with its operation. Complete details may be obtained by referring to the previous paper.[1]

The bridge is shown in Fig. 1. The two coils for magnetizing the specimens are marked Z_x and Z_s respectively. R_2 is a fixed resistance, and R_1 a variable resistance of the slide wire type. The galvanometer used was a Leeds & Northrup pointer type alternating-current galvanometer, with a separately excited field winding.

[1] W. B. Kouwenhoven and A. C. Seletzky, "The Unbalanced Alternating Current Bridge for Magnetic Analysis," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part II, p. 298 (1930).

Two specimens alike in quality and area are placed, one in each coil, and the voltage across the bridge terminals adjusted to give the desired current through the coil containing the standard specimen. The bridge is then balanced by adjusting the variable resistance R_1. Under this condition the bridge balance is independent of the phase of the galvanometer field. The full size specimen is now withdrawn from the test coil, and another specimen of the same magnetic properties and length, but of different area is inserted in its place. The resulting galvanometer deflection is then reduced to zero by varying the phase setting of the galvanometer field. This setting of the galvanometer field is called θ_x, and is a function both of the flux and of the loss in the specimen.

The bridge is now ready for operation. The voltage across it is kept constant and the specimens to be tested are inserted in turn in the test coil. Any variation in the value of R_1 for balance indicates that the unknown specimen differs from the standard.

The use of the standard specimen may be omitted, and a coil alone used in its place, provided other means are available for balancing the bridge. This avoids the possibility of heating of the standard specimen and the consequent changes that may take place in its characteristics. However, by proper design of the magnetizing winding a standard specimen may be safely used.

In addition to the θ_x reading, it is possible to obtain a different setting of R_1 for balance for each position of galvanometer field. The two most important observations are, first, the flux setting θ_M, where the change in the value R_1 is a measure of the difference in flux in the two specimens, and second, the loss setting θ_L, where the change in R_1 is a measure of the difference in the losses. Readings obtained at these two settings proved to be of great value in the study of the magnetic properties and heat treatment of the specimens.

FLUX PENETRATION

Magnetic analysis by the use of alternating flux involves two factors, permeability and losses. In addition, the penetration of the flux into the material must be considered. This phenomena, known as the "skin effect" was suggested by L. W. McKeehan[1] as a possible explanation of the operation of the unbalanced alternating-current bridge, with the galvanometer field in the θ_x position.

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[1] Discussion by L. W. McKeehan of paper by W. B. Kouwenhoven and A. C. Seletzky on "The Unbalanced Alternating Current Bridge for Magnetic Analysis," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part II, p. 312 (1930).

When a solid steel specimen is subjected to an alternating magnetizing force, the flux sets up eddy currents in the material. The action of the eddy currents cause a weakening of the alternating-current flux. This action will be a maximum at the center of the specimen and results in a concentration of the magnetic flux toward the outer layer. The flux density throughout the specimen is, therefore, not uniform. Skin effect is usually expressed as the penetration of the flux at surface density into the specimen, which gives the same total flux as actually exists.

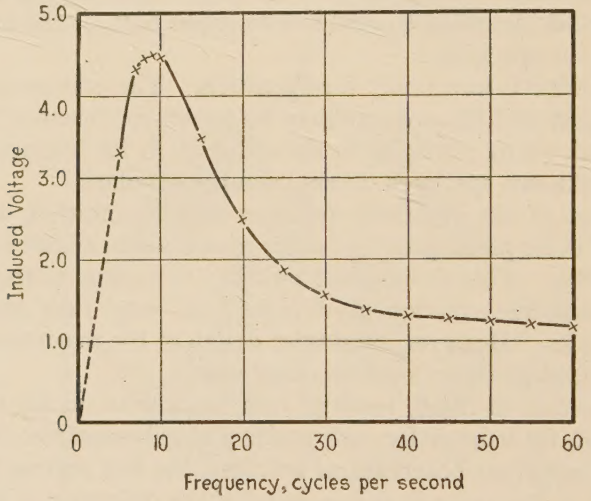

FIG. 2.—Flux Penetration Phenomena, Magnetizing Force Constant.

The distance of penetration of flux into a steel specimen is given by the well-known fundamental equation:

$$\sigma = K\sqrt{\frac{\rho}{\mu f}}$$

where ρ = specific resistance of specimen,
σ = penetration in centimeters,
K = constant,
μ = permeability of specimen, and
f = frequency.

It is seen from these relations that the total thickness is not a contributing factor with regard to total flux present. On the other hand, the thinner the specimen, the greater will be the relative penetration and the more uniform the flux density throughout. With a

given thickness of specimen, the penetration will remain the same, with constant frequency independent of cross-sectional area.

In order to determine if the phenomena of "skin effect" was present to a marked degree in the knife blade specimens used in this investigation, their magnetic characteristics were studied at a constant magnetizing force of variable frequency. Specimens of the same stock, thickness and heat treatment as the knife blades were tested in the laminated Fahy Simplex permeameter.

The voltage induced in the "*B*" coil of the permeameter was measured at a constant magnetizing force for a wide range of frequencies. Assuming that the permeability is independent of frequency as has been shown by Alexanderson[1] and others, the induced voltage would be directly proportional to the frequency if no skin effect were present.

Results of this work are shown in Fig. 2. It is evident that the flux penetration is uniform up to a frequency of approximately seven cycles per second for the condition of the test. The induced voltage reaches a maximum at nine cycles. Beyond this point the total flux threading the specimen decreases as the frequency is increased. This curve also shows that at the higher frequencies the net flux is approximately constant.

This curve (Fig. 2) shows definite evidence of the phenomenon of skin effect in the steel knife blade specimens which have a maximum thickness of 0.1 in. The results, therefore, indicate that flux penetration is a factor in the operation of the unbalanced alternating-current bridge with specimens differing in cross-sectional area.

DEVELOPMENT

In addition to the knife blades mentioned in the previous paper, another group of blades was studied. This group of blades, known as lot C, was submitted by the Winchester Repeating Arms Co. and consisted of 26 unknown blades marked A to Z, inclusive, and a group of seven standard blades marked S-1 to S-7, inclusive. The 26 unknown blades included some with softened points and some others with slight differences in heat treatment. These blades were tested in the original bridge and their separation was so slight that no data concerning the correlation between their magnetic characteristics and heat treatment were published.

The authors were not satisfied with the results obtained and, therefore, studied the bridge and its operation further. The outcome

[1] E. F. W. Alexanderson, "Magnetic Properties of Iron at Frequencies up to 200,000 Cycles," *Transactions*, Am. Inst. Electrical Engrs., Vol. 30, Part III, p. 2433 (1911).

of this study led to a very much improved segregation of the 26 unknown blades into their respective groups and shows definite correlation between bridge readings and heat treatment.

The first improvement was obtained by operating the bridge at constant voltage instead of constant current, as suggested in the first paper. The next step was to obtain the complete circle diagram of the bridge, experimentally. This is given in the Appendix to this paper.

The bridge was then studied as a four arm inductance bridge and the values of the impedance in its arms brought into agreement with the conditions for maximum sensitivity. This study also brought to light certain relations that applied to the impedance of the bridge arms. Next the effect of wide variations in magnetomotive force upon the separation of the specimens was investigated. Finally the results of these studies were combined and produced an improved unbalanced alternating-current bridge, which gives definite indications of variation in heat treatment of specimens, independent of their cross-sectional area.

CONSTANT VOLTAGE OPERATION

The unbalanced alternating-current bridge as previously presented used a constant current through the specimen test coil for specimens of all sizes and permitted the current to vary through the standard test coil. This method, while working satisfactorily, presents the practical difficulty that the bridge voltage varies for each specimen. This fact would be undesirable in commercial application. After an extensive investigation it was found that the unbalanced alternating-current bridge with some minor changes separated steel specimens of various heat treatments to an even better degree when the voltage was maintained constant across the entire bridge. This method of operation maintains the current through the standard test coil constant, while the current through the specimen test coil now varies as the specimen deviates from the standard.

When the voltage is held constant across the bridge, the voltages and currents in the bridge vary in accordance with the circle diagram relations of a series circuit containing resistance and reactance. The values of the voltages and currents in the bridge arms were determined for full, one-half, and quarter size specimens and are plotted in the circle diagram of the bridge. This diagram is shown in Fig. 4 in the Appendix.

IMPEDANCE OF BRIDGE ARMS

A study of the circle diagram of the alternating-current bridge shows the voltage across the test coil to be very much greater in value

than the voltage on the resistance arms of the bridge. It is a well-known fact that if the voltages on the four arms of the bridge are of the same value, the sensitivity of the combination will be a maximum. To accomplish this either the impedance of the test coils must be decreased, or the value of resistance in the resistance arms of the bridge must be increased.

In an endeavor to decrease the resistance of the test coils, new coils of 720 turns of No. 16 D.C.C. wire were built. The resistance of each coil was 1.5 ohms (direct current) and the inductance 7.3 millihenries without the specimen in place, and 10.6 millihenries with the standard specimen. These coils, which were designated as coils Nos. 3 and 4, respectively, had a lower impedance than the ones used in the previous work. The lower impedance of these coils gave voltages of approximately the same order of magnitude on all arms, but the sensitivity of the bridge was decreased due to the large leakage flux and the low effective magnetizing force. As the resistance of a coil is decreased, its leakage flux increases due to the larger size wire needed. Results mentioned in a later part of this paper show that a large magnetomotive force is necessary if increased separation of specimens is to be obtained.

To increase the flux density in the knife blade specimens, another set of coils was constructed, each of 1920 turns of No. 24 D.C.C. wire. These coils, Nos. 5 and 6 respectively, each had a resistance of 18.2 ohms (direct current) and an inductance of 32.6 millihenries without the specimen, and 83.8 millihenries with the standard specimen in place. The resistances of the R_1 and R_2 arms of the bridge were increased until the voltages across the four arms were of the same order of magnitude. Increased sensitivity and separation was evident at once for this circuit as compared to other bridge arrangements.

The high value of resistance of test coils Nos. 5 and 6 might first be considered as a detriment to the operation of this method, but such is not the case. It must be remembered that this alternating-current bridge measures the difference in the losses between specimens in the two test coils, and when both coils contain similar specimens in every respect, all the losses in one side of the bridge are balanced by those in the other side. When specimens of different characteristics are tested, the bridge reading is a measure of their difference.

After constructing the coils they were adjusted so as to give equal magnetizing forces for the same current values and were also made equal in resistance. After the test coils were thus balanced the bridge readings were independent of the phase of the galvanometer field for a specimen which had indentical characteristics and dimensions with those of the standard.

MAGNETOMOTIVE FORCE

The value of the magnetomotive force that will give the best separation of specimens varies with the material. Using test coils Nos. 5 and 6 and two knife blade specimens S-1 and A, the effect of varying the exciting current was studied. The result of this test showed that the best operating conditions were obtained when a current of 0.6 ampere flowed through the 1920 turns of the solenoid. This gave the largest separation between the specimens, that is, the maximum difference in their R_1 settings for balance.

TABLE I.—RESULTS OF MAGNETIC ANALYSIS TESTS ON KNIFE BLADES.

Blade	Brinell Hardness Numbers			θ_x Separation, R_1 Reading	Blade	Brinell Hardness Numbers			θ_x Separation, R_1 Reading
	Heel	Middle	Point			Heel	Middle	Point	
STANDARD GROUP: DRAWN AT 450° F. FOR 30 MINUTES.									
S-1	592	623	592	....	S-6	592	623	592	....
S-2	592	592	592	....	S-7	592	592	592	....
S-5	572	592	572	....					
GROUP I: STANDARD HEAT TREATMENT.									
D	572	592	592	5	U	572	592	572	−9
V	592	623	623	7	X	592	623	592	−10
I	572	592	592	0	G	...	...	...	5
GROUP II: STANDARD HEAT TREATMENT. POINTS OF BLADES THEN HEATED FOR ½ IN. TO A RED COLOR IN A LEAD BATH AND COOLED IN AIR.									
S	592	592	355	−39	M	592	592	408	−30
R	592	592	396	−28	N	592	592	341	−27
J	623	592	396	−44					
GROUP III: DRAWN AT 950° F. FOR 30 MINUTES.									
A	396	396	396	169	W	396	396	396	173
B	396	408	396	167	Z	396	408	408	170
K	408	408	408	169					
GROUP IV: DRAWN AT 850° F. FOR 30 MINUTES.									
C	426	426	426	137	P	426	426	426	145
F	426	426	426	146	Y	426	426	426	141
L	426	426	426	143					
GROUP V: DRAWN AT 650° F. FOR 30 MINUTES.									
E	519	519	519	59	Q	503	519	503	45
H	519	519	519	61	T	519	503	503	55
O	503	519	519	48					

RESULTS

The results of the described investigations all point to means of improved sensitivity of the bridge and increased separation between specimens, and therefore it was only necessary to take advantage of these improvements and construct a new alternating-current birdge. This was done, using coils of improved design to give greater flux density in the specimen. Constant voltage was used across the bridge in order to obtain better operation and further, the values of the bridge arms were so adjusted as to give voltages of the same order of

magnitude across all of them. Preliminary tests showed large increases in separation of steel speimens over those obtained in the first work published on this subject.

Many tests were conducted on this bridge, and a characteristic group of data is shown for one complete run on the knife blade specimens mentioned above. They were in the rough state before grinding and differed slightly in cross-sectional area. The blades were stamped on the tang, alphabetically from A to Z, and had received various

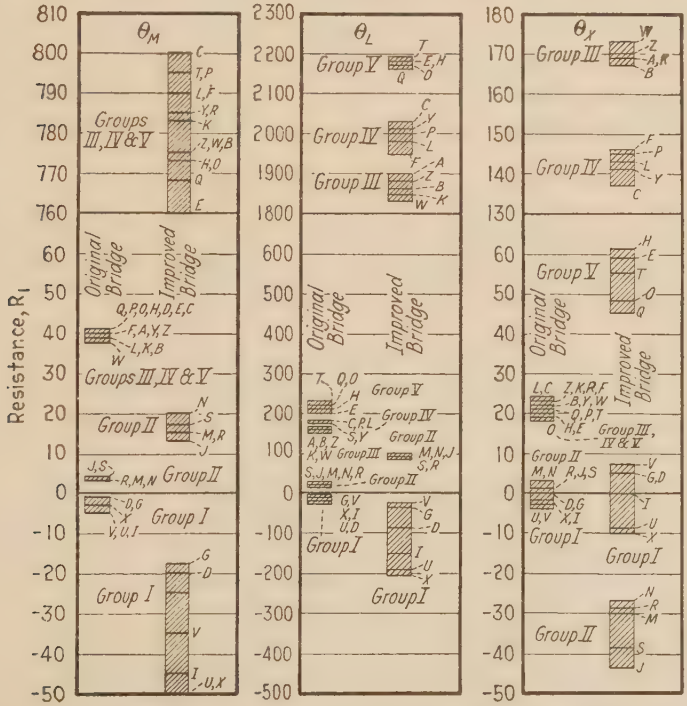

FIG. 3.—Separation of Specimens of Varying Heat Treatment. Specimen S-1 Used as Standard.

heat treatments. In addition to this lot of blades, was a group of seven blades stamped S-1 to S-7, which had received the standard heat treatment and had the standard degree of hardness. Specimen S-1 was used as a standard and specimen S-3 was reduced to approximately one half cross-sectional area. The latter specimen was used in establishing the galvanometer phase position θ_x. These knife blades had approximately the same dimensions as those mentioned in the previous paper. For this test the bridge was operated at 35 volts, 60 cycles.

The heat treatment, Brinell hardness number at three locations, and the bridge reading at the θ_x setting of each specimen are given in Table I. The knife blade stock had been quenched at 1550° F. before receiving the heat treatment indicated. The blades fall into five groups, as may be seen from Table I.

The results are given in Fig. 3 of the bridge readings obtained as the flux setting, θ_M, at the loss setting, θ_L, and at the combination setting θ_x, of the galvanometer field. In order to show clearly the improvements that have been realized, the values obtained with the original bridge a year ago are included in the figure. A study of this figure shows that the separation between the specimens of different heat treatments has been increased at the θ_M galvanometer setting roughly twenty times, at θ_L about ten times, and at θ_x some eight times.

SUMMARY

It is evident that skin effect is present in the knife blade specimens and its action contributes to the successful operation of the bridge when the galvanometer field setting is at the combination position, θ_x.

Greatly increased sensitivity is made possible by the use of the proper values of resistances and inductances in the bridge arms. The resistance and inductance of the standard coil must balance those of the unknown coil.

For any given specimens the best value of the magnetomotive force may be easily determined by test. In winding magnetizing solenoids for use in an alternating-current bridge, the resistance may be any value consistent with safe heating, because the bridge reading is a measure of the difference between specimens.

The bridge in its improved form not only separates the good specimens from those that have received improper treatment but also divides them into distinct groups, in line with both their heat treatments and Brinell hardness numbers.

APPENDIX

Circle Diagram:

The circle diagram, Fig. 4, was obtained from measurements of the voltages and currents in the original bridge using specimens differing in area, but of identical magnetic characteristics. The lettering on the vector diagram is the same as that of Fig. 1. In Fig. 4, AD is the voltage across the bridge. The vector AC is the drop across the standard coil, Z_s; CD the voltage drop across the resistance R_2.

With identical specimens in the two coils, the voltage drop AB, across the unknown, coincides with AC; and also BD, the drop across R_1, falls on CD.

That is, the points C and B coincide when the bridge is perfectly balanced When the unknown specimen has a cross-section different from that of the standard, the point B no longer coincides with C. The new location of the point B is shown by the crosses for a one-half size specimen in the Z_x coil for

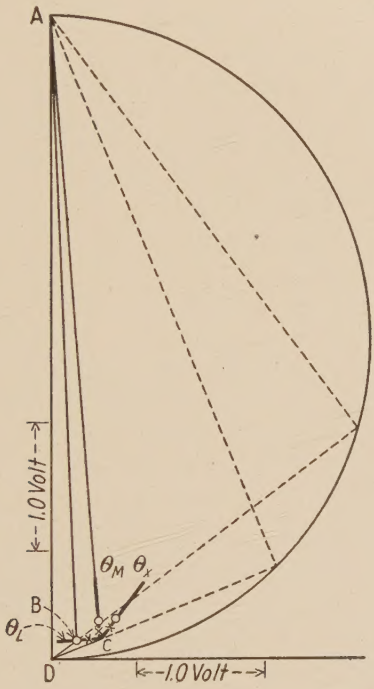

FIG. 4.—Circle Diagram of Bridge Circuit, Applied Voltage Constant.

each of the three positions θ_M, θ_L and θ_x of the galvanometer field. The points shown by the circles are the corresponding positions for a one-quarter size specimen. It is evident that with specimens of unequal areas, the point B must be brought to its proper location for zero deflection of the galvanometer at the given phase setting by adjusting the variable resistance R_1.